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PATENT TRADEMARK OFFICE

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**NON-UNIFORM THICKNESS ELECTROACTIVE DEVICE**Claim of Benefit of Provisional Application

5 Pursuant to 35 U.S.C. §119, the benefit of priority from provisional application 60/161,113, with a filing date of October 22, 1999, is claimed for this non-provisional application.

1c913 U.S. PTO  
09/696526  
10/23/00

Cross Reference to Related Cases

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This application is related to co-pending, commonly owned patent application Serial No. \_\_\_\_\_, filed October 23, 2000, entitled "Polymer-Polymer Bilayer Actuator", co-pending, commonly owned patent application Serial No. \_\_\_\_\_, filed October 23, 2000, entitled "Electrostrictive Graft Elastomers", and co-pending, commonly owned patent application Serial No. \_\_\_\_\_, filed October 23, 2000, entitled "Membrane Position Control."

Origin of the Invention

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The invention described herein was made by an employee of the United States Government and a National Research Council Research Associate and may be used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

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Background of the Invention1. Field of the Invention

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The present invention is generally related to the field of electroactive actuators. More specifically, it relates to an electroactive actuator having at least one layer of non-uniform thickness.

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2. Description of the Related Art

Actuation devices are used for many applications, including aerospace, fluid flow and biomedical. Space applications include robotics, miniature rovers, and the shaping, tuning, positioning, controlling and deforming of membrane structures. Membrane inflatable and deployable space structures are used by the government and commercially as reflectors, antennas, solar arrays, satellites, solar sails, etc. Although actuation devices are widely used, many challenges exist which limit their performance for high precision applications. Factors affecting precision include surface smoothness, deviation from desired surface profile, surface deformations due to thermal fluctuations, and accurate membrane positioning. Additionally, hydrofoils and airfoils that can optimize their surface shape at varying flow rates are desirable to, for example, increase lift, reduce noise levels, lower vibrations and reduce drag. Other potential uses of actuation devices include precise positioning of display panels and optical index layers. To operate most effectively in the aforementioned applications, actuation devices require sufficient force and strain, and often need to produce complex motions that may include both bending and torsion.

Conventional piezoelectric ceramic, polymer, and composite actuators (including piezoelectric, electrostrictive, and electrostatic) lack the combination of sufficient strain and force to most effectively perform the aforementioned functions. Previous concepts for shaping and tuning membrane structures have primarily involved the use of piezoelectric ceramic materials. These ceramic piezoelectrics have the major problems of large mass, high density, low strain and high brittleness. Generally, piezoceramics also need additional mechanical devices to achieve a shaping, tuning, positioning, controlling or deforming function. In contrast to electroceramics, electroactive polymers are emerging as new actuation materials due to their enhanced strain capabilities.

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Electrostrictive polymer-polymer actuators or other electroactive polymer actuators that provide enhanced strain capabilities can shape, tune, position, control and deform membrane structures, as well as perform in other applications, in ways not previously possible with other materials. An

5 example of such an electrostrictive polymer-polymer actuator is described in the patent application entitled "Polymer-Polymer Bilayer Actuator", Serial No. \_\_\_\_\_, filed October 23, 2000, hereby incorporated by reference.

The greater strain capability provides further possibilities for small-scale applications and integration into skin surfaces. The electroactive actuators  
10 can coincide with specific contours to optimize, for example, shapes for fluid flow, reflection and other membrane uses.

Existing devices capable of providing complex motion response utilize surface electrode patterning and/or polymer laminates having tailored lamina properties and orientations, such as described in U.S. Patent Number  
15 4,868,447. It is desirable to obtain complex motion response without requiring tailored surface electroding or laminate design.

#### Statement of the Invention

20 Accordingly, an object of the present invention is to provide an electroactive device having controlled local strain and curvature.

Another object is to provide an electroactive device having a response contour which varies across the device.

Another object is to provide an electroactive device that can produce  
25 complex motions.

A further object is to provide an electroactive device with enhanced strain capabilities.

Additional objects and advantages of the present invention are apparent from the drawings and specification that follow.

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Summary of the Invention

In accordance with the present invention, the foregoing and other objects and advantages are attained by providing an electroactive device having at least two layers of material, wherein at least one layer is an electroactive material and wherein at least one layer is of non-uniform thickness. The device can be produced in various sizes, ranging from large structural actuators to microscale or nanoscale devices. The applied voltage to the device in combination with the non-uniform thickness of at least one of the layers (electroactive and/or non-electroactive) controls the contour of the actuated device. The effective electrical field is a mathematical function ( $E = V/D$ , where  $E$  is electrical field,  $V$  is voltage and  $D$  is thickness) of the local layer thickness. Therefore, the local strain and the local bending/torsion curvature are also a mathematical function of the local thickness. Hence the thinnest portion of the actuator offers the largest bending and/or torsion response. Tailoring of the layer thicknesses can enable complex motions to be achieved.

In a preferred embodiment, one or more electroactive layers of non-uniform thickness control the curvature of the device. The most responsive portions of the device will be at the thinnest portions of the electroactive layers, where the highest electric fields result. In other embodiments, the curvature can be controlled by varying the thickness of the non-electroactive layer or by varying the thickness of both the electroactive layer(s) and non-electroactive layer.

The electroactive device described herein will provide enabling technology to allow variable contouring of the device to expand electroactive actuator use in applications such as motion control, position control, tension control, curvature control, biomedical pulse control, surface flow dynamic control, display panels, optical alignment, optical filters, micro-electromechanical systems, and nano-electromechanical systems. More specifically, it can be utilized in membrane inflatable and deployable

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structures, and be used for shaping surfaces such as hydrofoils and airfoils to optimize shape for different flow rates. Furthermore, the device could serve to provide precise positioning of an optical index layer for a liquid crystal display and provide positioning control of display panels to reduce glare.

5 Advantages of using polymers for the electroactive layer(s) include low weight, unified materials-device body, simple operation, long lifetime, flexibility, toughness, and ease of processing. However, use of layers (electroactive and/or non-electroactive) of non-uniform thickness to control the curvature can be applied to any materials that can cooperatively produce  
10 a sufficient force and strain combination for particular shaping, tuning, positioning, controlling and deforming applications.

#### Brief Description of the Drawings

15 A more complete appreciation of the invention and the many of the attendant advantages thereof will be readily attained as the same becomes better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIGs. 1A illustrates a side view of an embodiment of a non-uniform  
20 thickness actuator, showing the most responsive portions located at the thinnest points of the active layer closer to the free end.

FIG. 1B illustrates a side view of an embodiment of a non-uniform thickness actuator, showing the most responsive portions located at the thinnest points of the active layer closer to the cantilevered end.

25 FIG. 2 illustrates a side view of a non-uniform thickness actuator fixed at one end, with the thickness of the active layer decreasing towards the fixed ends.

FIGs. 3A-3C illustrate a cross section of a typical hydrofoil or airfoil with a non-uniform thickness actuator, in actuated and non-actuated  
30 configurations, attached to the surface of the foil.

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FIG. 3D illustrates a cross section of a typical hydrofoil or airfoil with a non-uniform thickness actuator integrated into the foil.

FIG. 4 illustrates an embodiment of a non-uniform thickness actuator having stacked electroactive layers, wherein the stacks on either side of the bond interface are alternately activated.

FIG. 5 illustrates an embodiment of a non-uniform thickness actuator having multiple electroactive layers.

#### Detailed Description of the Invention

Referring now to the drawings, and more particularly to FIGs. 1A and 1B, an electroactive device according to the present invention is shown and referenced generally by the numeral 100. Electroactive layer 112 is of non-uniform thickness and is bonded to non-electroactive layer 114, which has uniform thickness. A layer should be understood to be a sheet, strip, film, plate, or the like, which may have various configurations such as planar, annular, and spiral. Although either or both layers can be of nonuniform thickness, nonuniformity of the electroactive layer thickness will produce the greatest strain, and hence displacement capability of the device.

Electroactive layer 112 can be any material that responds to electrical activation, including a polymer, ceramic or composite, and is selected based upon the response desired. A preferred material is the electrostrictive graft elastomer described and claimed in "Electrostrictive Graft Elastomer", Serial No. \_\_\_\_\_, filed October 23, 2000, hereby incorporated by reference. Another preferred embodiment is the polymer-polymer actuator described and claimed in "Polymer-Polymer Bilayer Actuator", Serial No. \_\_\_\_\_, filed October 23, 2000, also hereby incorporated by reference, wherein the active polymeric web has non-uniform thickness. Non-electroactive layer 114 must have a mechanical modulus sufficient to obtain the desired response in conjunction with electroactive layer 112. For equal thickness of the electroactive layer 112 and non-electroactive layer

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114, the mechanical modulus of the non-electroactive layer 114 is preferred to be equal to or lower than the mechanical modulus of the electroactive layer 112 in order to achieve maximum bending displacement. Candidate materials include polymers, ceramics, composites, and metals.

5           The layers 112 and 114 are bonded using chemical, physical, mechanical, or biological bonding means. The preferred bonding means provide ease in processing, minimized thickness, as well as the desired stiffness and durability. Especially preferred is a chemical adhesive that is cast and cured at room temperature. The bonding layer thickness depends  
10           on the whole configuration of the device, including the material selections for the electroactive and non-electroactive layers, as well as the device's displacement and stress induced at the bonding interfaces. The thinnest bonding layer that satisfies the device requirements is preferred. Epoxy resin is a suitable chemical adhesive.

15           Layers 112 and 114 are fixedly mounted at 116 and electrically connected to a drive voltage (not shown). When no voltage is supplied, the device remains in the non-activated position 120. In Fig. 1A, when voltage is supplied, electrical signals are supplied across the thickness of layer 112, and the electroactive response of layer 112 causes device 100 to bend to  
20           position 140. The electrical signals are supplied via one or more electrodes 130 disposed on each of the upper and lower surfaces of layer 112. These electrodes 130 can be disposed via a single layer across the surface or via multiple or patterned electrodes, depending on the desired response. One example of suitable electrodes 130 are gold electrodes, although any  
25           material having significant conductivity (generally greater than  $10^5$  S/m) and fatigue resistance can be used. A conductive polymer having mechanical elasticity comparable to the electroactive material and good adherence to the electroactive material is preferred for the electrode material. Some examples of suitable electrodes are polypyrrole and polyaniline. The drive voltage is  
30           dependent on the number of device layers, as well as on the desired displacement, and can range from several volts to several kV.

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The most responsive area of device 100 is position 140 at the thinnest portion of electroactive layer 112. Similarly, in Fig. 1B, the most responsive area of device 100 is position 150, at the the thinnest portion of electroactive layer 112. In other embodiments the non-electroactive layer 114 may be of non-uniform thickness, although lesser displacement of the device would be achieved.

The thickness ratio between electroactive layer 112 and non-electroactive layer 114 can be tailored to achieve the desired response. If the electroactive and non-electroactive layers have the same mechanical modulus, then the non-electroactive layer thickness should be less than or equal to that of the electroactive layer thickness. If the moduli differ, the thicknesses are optimized based on the application requirements. The thickness of the layers 112 and 114 depend upon the desired response. For multiple electroactive layers, the thicknesses of the layers, the moduli of the layers, and the material selection is tailored to achieve desired results.

Referring to FIGs. 2A and 2B, another embodiment of the electroactive device according to the present invention is shown and referenced generally by the numeral 200. Electroactive layer 212 is narrowed at each end and is bonded along its length to non-electroactive layer 214, which has uniform thickness. Device 200 is fixedly attached at 280 to a structure 235 on which the actuator acts. Furthermore, device 200 can be attached to the support layer 235 by chemical or mechanical means. Electroactive layer 212 is electrically connected to a drive voltage (not shown). When no voltage is supplied, as illustrated in FIG. 2A, the device 200 remains in its non-activated position. When voltage is supplied, as illustrated in FIG. 2B, the electroactive response of layer 212 causes device 200 to bend to its activated position. The most responsive areas of the device 200 are at the thinnest portions of layer 212, nearest ends 280 and 290

FIGs. 3A through 3C depict an application in which a non-uniform electroactive device is used to optimize characteristics of a hydrofoil or airfoil. Such optimization may include the formation of traveling waves. Cross-



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section 300 represents a typical airfoil or hydrofoil. One or more non-uniform thickness electroactive actuators 310 are affixed to the airfoil or hydrofoil, preferably at the leading edge. In the activated positions 320 and 330, the actuators form a curvature that alters the flow stream 340. FIG. 3B illustrates the actuator displacement resulting from the actuator being fixed at 350 to the airfoil or hydrofoil. FIG. 3C illustrates an actuator displacement resulting from the actuator being fixed at 360 to the airfoil or hydrofoil. In another embodiment, shown in FIG. 3D, one or more electroactive devices 370 are integrated into the airfoil or hydrofoil; i.e., attached to and recessed within the hydrofoil or airfoil 300. Again, the electroactive devices are affixed at one end to the airfoil or hydrofoil. This embodiment results in a smooth airfoil/hydrofoil surface when the electroactive device(s) 370 are in their inactivated state.

FIG. 4 illustrates an embodiment having multiple electroactive layers 400 through 450. Electroactive layers 400 through 420 form a first stack 470 and electroactive layers 430 through 450 form a second stack 480. The first stack 470 and second stack 480 are bonded via bonding layer 460. First stack 470 and second stack 480 are alternately activated. Although electroactive layers 400 through 450 can be different materials, consistent materials are preferred to obtain greater control of the device.

FIG. 5 illustrates an embodiment having three electroactive layers 510 through 530 and a single non-electroactive layer 500. Such a multiple electroactive layer arrangement may be used to obtain greater output force and greater strain/displacement for a given drive voltage.

The thickness variation of one or more layers is chosen to achieve a desired contour. The thickness of a layer can vary as any function of length, any function of width, or as any function of both length and width. This thickness variation acts in cooperation with and/or enhances the contour that could be achieved by material choice, electrode design, or orientation of layers. The electroactive device

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Although the drawings illustrate specific configurations, the invention is not limited to such specific configurations. At least one electroactive layer is required and at least one non-uniform thickness layer (electroactive or non-electroactive) is required, but each desired application and its associated  
5 desired response (strain and force) will dictate the number of electroactive layers and number of nonuniform layers needed. A non-electroactive layer is not required, such as the embodiment shown in FIG. 4 illustrates; however, if a non-electroactive layer is used, there should be no more than one. As provided earlier, such non-electroactive layer may be of uniform or non-  
10 uniform thickness depending on the desired results. Although the embodiments shown illustrate the electroactive devices being fixed at an end, they may be fixed to another location as desired for a specific application. For example, the electroactive device itself could be the membrane to be deformed, such as a reflector, and have a centrally fixed point.

15 Factors which affect the performance of the present invention include:  
1) the non-uniformity in layer thicknesses; 2) electromechanical properties of the electroactive layer, such as electric field induced strain, mechanical modulus, and electromechanical conversion efficiency, as well as output energy/energy density; 3) mechanical properties of the non-electroactive  
20 layer, such as mechanical modulus; 4) bonding between the layers, as well as 5) the geometric dimension of each component. For an optimized configuration; 1) the electroactive layer(s) offer maximized electric field induced strain and maximized mechanical modulus, therefore, maximized electromechanical output power/energy; 2) the non-electroactive layer offers  
25 mechanical modulus not higher than that of the electroactive layer(s); 3) the bonding between layers offers strength, does not allow any significant sliding effect between the electroactive and non-electroactive layers in the direction parallel to the surfaces, and offers maximized durability under working conditions; 4) the relative dimensions of the electroactive layer(s) and non-  
30 electroactive layer are chosen according to the requirements of a particular application, with a relatively thin non-electroactive layer being preferred; 5)

the thickness of the bonding material is minimized; and 6) the non-uniform thicknesses of layers are designed to meet desired response requirements.

Obviously, numerous additional modifications and variations of the present invention are possible in light of above teachings. It is therefore to be understood that within the scope of the appended claims, the invention may be practiced otherwise than is specifically described herein.

What is claimed is:

[illegible]